

ANTENNA COUNT FOR MASSIVE MIMO: 1.9 GHz VERSUS 60 GHz

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Abstract

If we assume line-of-sight propagation and perfect channel state information at the base station – consistent with slow moving terminals – then a direct performance comparison between single-cell Massive MIMO at PCS and mmWave frequency bands is straightforward and highly illuminating. Line-of-sight propagation is considered favorable for mmWave because of minimal attenuation, and its facilitation of hybrid beamforming to reduce the required number of active transceivers. We quantify the number of mmWave (60 GHz) service antennas that are needed to duplicate the performance of a specified number of PCS (1.9 GHz) service antennas. As a baseline we consider a modest PCS deployment of 128 antennas serving 18 terminals. We find that, to achieve the same per-terminal max-min 95%-likely downlink throughput, 10000 mmWave antennas are needed. To match the total antenna area of the PCS array would require 128000 half-wavelength mmWave antennas, but a much reduced number is adequate because the large number of antennas also confers greater channel orthogonality. The principal alleged benefit of mmWave technology – vast amounts of inexpensive spectrum – is at least partially offset by the complexity of possibly unwieldy amounts of hardware.

1 Introduction

Massive MIMO [1, 2] and millimeter-wave (mmWave) communications [3–7] are the two main physical-layer techniques considered for wireless access in 5G and beyond. The superiority of one over the other has been the subject of much public debate, most recently, in the Globecom 2016 industry panel “Millimeter wave versus below 5 GHz Massive MIMO: Which technology can give greater value?”, summarized in [8]. The object of this paper is to quantitatively compare the two technologies in a scenario where uncontested models of the physical propagation channels exist: a single cell with line-of-sight between the terminals and the base station, and very low terminal mobility.

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1.1 Massive MIMO Below 5 GHz

Massive MIMO relies on the use of large antenna arrays at the base station. In TDD operation, each base station learns the uplink channel responses to its served terminals through measurements on uplink pilots. By virtue of reciprocity of propagation, these estimated responses are valid also in the downlink. Based on the estimated channels, the base station performs multiuser MIMO decoding on uplink and precoding on downlink. In FDD operation, in contrast, downlink pilots and subsequent feedback of channel state information from the terminals are required.

Fundamentally, the permitted mobility is dictated by the dimensionality of the channel coherence interval – that is, the coherence bandwidth in Hertz multiplied by the coherence time in seconds. In a TDD deployment, the coherence interval determines how many terminals that may be multiplexed, because all terminals must be assigned mutually orthogonal pilot sequences that shall fit inside of this coherence interval. In an FDD deployment, the coherence interval dimension limits both the number of base station antennas (as each antenna needs to transmit an orthogonal pilot) and the amount of channel state information that each terminal can report.

The main argument in favor of Massive MIMO deployments using carrier frequencies below 5 GHz is its fundamental feasibility to perform aggressive spatial multiplexing under high terminal mobility, at least in TDD operation, as proven both by information-theoretic calculations [1] and by practical experiments [8,9]. In addition, below 5 GHz diffraction is significant and electromagnetic waves penetrate non-metallic objects and foliage well – enabling the coverage of wide areas both indoors and outdoors.

1.2 mmWave Communications

Millimeter Wave communications typically refers to wireless operations in the band between 30 and 300 GHz. Its feasibility has been demonstrated in practice, for example, using beam-tracking algorithms in a small-cell environment [10] and horn antennas for transmission in rural areas [11].

Compared to sub-5 GHz bands, the physics at mmWave bands is different in several respects:

- The effective area of an antenna with fixed gain pattern scales proportionally to $1/f_c^2$, where f_c is the carrier frequency [12]. Considering the uplink for the sake of argument, this means that for a given power radiated by the terminal, the number of base station antennas required to maintain a predetermined link budget scales proportionally to f_c^2 . Consequently, either massive arrays, or directive antenna elements, are needed to facilitate transmission over large distances.

- mmWaves do not penetrate solid objects well, and propagation is dominated by the presence of unobstructed direct paths and specular reflection. This implies that mmWave links are likely to be operating in conditions either with line-of-sight, or a few reflections, between the base station and the terminal.
- The Doppler frequency, and hence the dimensionality of the channel coherence interval, scales proportionally to $1/f_c$. This implies difficulties for the multiplexing of many terminals at high mobility, due to the insufficient room for transmission of pilots (and channel state information feedback in FDD).

Fortunately, as the propagation becomes increasingly line-of-sight, the acquisition of complete channel responses, for the purpose of precoding and decoding, is not necessary. The identification of a line-of-sight path, potentially combined with a few reflected paths, is sufficient in order to obtain channel estimates that are sufficiently accurate.

The standard argument in favor of mmWave communications is the availability of huge bandwidths. While this is certainly correct, the use of increased bandwidths also entails an increase in radiated power. Specifically, by the Shannon-Hartley formula, capacity scales as $B \log_2(1 + P/(BN_0))$, where B is the bandwidth in Hertz, P is the received power in Watt, and N_0 is the noise spectral density in Watt/Hertz. Hence, a doubling of the bandwidth requires a doubling of the radiated power in order as well, in order to achieve a capacity scaling proportional to the bandwidth. For example, with a nominal radiated power of 10 Watt over a bandwidth of 20 MHz, a radiated power of 500 Watt is required over 1 GHz.

2 Sub-5 GHz versus mmWave Comparison

While the use of mmWave carriers requires large antenna arrays to recover the loss incurred by smaller effective antenna element areas, the larger number of antennas also yields improved channel orthogonality. Specifically, the probability that two channel responses are similar decreases sharply when increasing the number of antennas in the array. This results in a new, intriguing tradeoff, if the multiplexing of many simultaneous terminals is of interest, and the provision of uniformly good quality of service in the cell is of concern. Nominally, considering only the path loss, $(60/1.9)^2 \approx 1000$ times more antennas would be required at mmWave (60 GHz) as compared PCS (1.9 GHz) to maintain the same link budget. However, in a scenario where many terminals are spatially multiplexed, the PCS system may be at disadvantage because its smaller number of antennas renders it much more likely that some terminal must be dropped from service due to channel non-orthogonality. Thus, the proportionate number of extra antennas required for the mmWave carrier may be considerably smaller than 1000. This effect is particularly pronounced under line-of-sight conditions [1, Section 7.2.3].

The following discussion will address the specific question: For a predetermined quality-of-

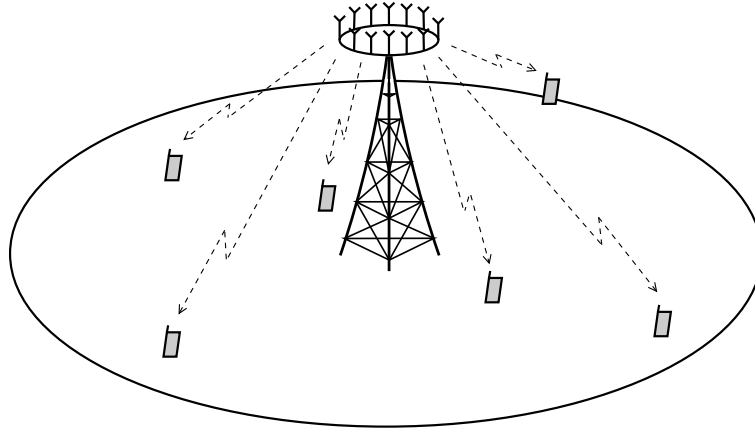


Figure 1: Single cell with circular base station array and line-of-sight to all terminals..

service, how many more antennas will a mmWave system require, compared to the PCS system? In detail, the setup is as follows:

- A single cell is considered, served by a circular base station array comprising M antennas at half-wavelength ($\lambda/2$) spacing, placed along a circle (Figure 1). The array diameter (aperture) is $d = M\lambda/(2\pi)$. A number of terminals are placed uniformly at random inside the cell, and multiplexed simultaneously in the same time-frequency resource.
- There is negligible mobility. This enables the base station to learn the channel responses with arbitrarily good accuracy, and it makes outage capacity a legitimate performance measure. This assumption also, substantially, eliminates the distinction between TDD and FDD mode operation.
- Zero-forcing decoding and precoding are performed at the base station, and max-min fairness power control is applied, ensuring that every terminal enjoys the same effective signal-to-noise-and-interference ratio (SINR). The justification for the use of zero-forcing over maximum-ratio processing is that performance increases significantly. Also, efficient hardware implementations are feasible and have been demonstrated in practice for reasonably-sized systems [13].
- Consistent with the no-mobility assumption, effective SINRs are obtained conditioned on the locations of the terminals – with thermal noise constituting the only source of randomness. Since there is perfect CSI, pertinent formulas for the effective SINR follow straightforwardly from a standard multiuser MIMO signal model. The max-min optimal power control policy is derived using the same principles as in [1, Chap. 5], and is detailed in [14]. The probability that a prescribed SINR target is not simultaneously met by all terminals in the cell is then computed numerically.

Number of simultaneously multiplexed terminals	18
Distribution of terminal locations	uniform within circular cell
Cell radius	500 m
Base station height over ground	30 m
Propagation model	line-of-sight (Friis free-space equation)
Base station antenna element gain	0 dBi
Terminal antenna gain	0 dBi
Power control	max-min SINR fairness (uniform quality-of-service)
Bandwidth	20 MHz
Terminal height over ground	1.5 m
Base station radiated power (downlink)	10 W
Terminal radiated power (uplink)	200 mW
Base station noise figure	9 dB
Terminal noise figure	9 dB

Table 1: Parameters in the numerical results.

Table 1 quantitatively summarizes all relevant parameters used in this case study. We adopt isotropic antenna gains of 0 dBi solely for simplicity. A more realistic model would, of necessity, have directional dependence which would introduce an additional random component to the propagation, e.g., the orientation of the terminal antenna.

Figure 2 shows the cumulative probability distribution of the effective SINR on uplink respectively downlink, for the PCS and mmWave systems. All randomness originates from the random terminal locations. The PCS system has 128 antennas and the mmWave system has 10000 antennas. In Figure 2, the 95%-likely downlink SINR (approximately 40 dB) is comparable for both systems. The mmWave system has 78 times more antennas than the PCS system. This is substantially less than predicted by a path-loss analysis ($(60/1.9)^2 \approx 1000$ times). The reason is the improved orthogonality conferred by the larger number of antennas at mmWaves. This improved orthogonality is also reflected by the increased steepness of the curves.

Table 2 shows the required number of base station antennas, and the corresponding array diameter, for different 95%-likely uplink SINRs. The mmWave array comprises a fairly large number of antennas but is geometrically rather compact. On downlink, fewer antennas are required in either case (not shown in the table).

The following remarks are in order:

- The 95%-likely SINR targets in Table 2 range from moderate to very high. From a purely information-theoretic point of view, for a given SINR, $\log_2(1 + \text{SINR})$ bits/s/Hz could

be achieved. However, for the high SINR values, the resulting modulation scheme would require large constellation sizes and therefore become very sensitive to phase noise.

- There is no interference, neither within the cell (owing to the perfect-CSI assumption), nor from other cells (owing to the single-cell assumption).

The modeling of intercell interference would be non-trivial under the adopted line-of-sight assumptions, because even though propagation within the cell is line-of-sight, interference from other cells may not be. However, at low mobility, pilot interference may be neglected and only noncoherent interference remains. Qualitatively, its impact on the SINR is comparable to the presence of extra thermal noise [1, Chap. 4].

- Performance on downlink is better than on uplink. This is expected, as more power is spent on the downlink. In Figure 2(a), the median difference between downlink and uplink is about 7.5 dB, and with 1% probability, it is about 14 dB. In Figure 2(b), the 1%-likely gap is smaller, since the channel orthogonality improves with increasing number of antennas.

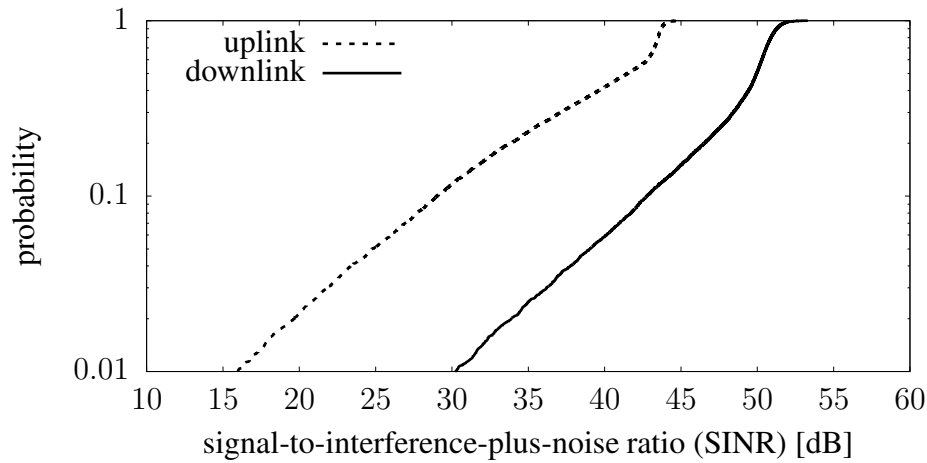
Hypothetically, if all channels were orthogonal and all terminals were subject to the same path loss, the uplink-downlink SINR difference would be equal to the power imbalance between downlink and uplink, $10/(18 \times 0.2) \approx 2.78 \approx 4.4$ dB. (Note that on downlink, the power is shared among all terminals.) With large path loss discrepancies, on the other hand, almost all power would be spent on the most disadvantaged terminal and the gap (with orthogonal channels) would be close to the upper bound $10/0.2 = 50 \approx 17$ dB.

- Arguably, the results are somewhat pessimistic since the max-min fairness power control criterion forces the simultaneous service of every terminal in the cell with the same SINR. If two terminals are located close to one another (with nearly the same direction-of-arrivals), then the resulting channel is ill-conditioned and much power needs be expended to invert it. Better performance could be obtained by scheduling one of those terminals on an orthogonal resource (for example, a different subcarrier).

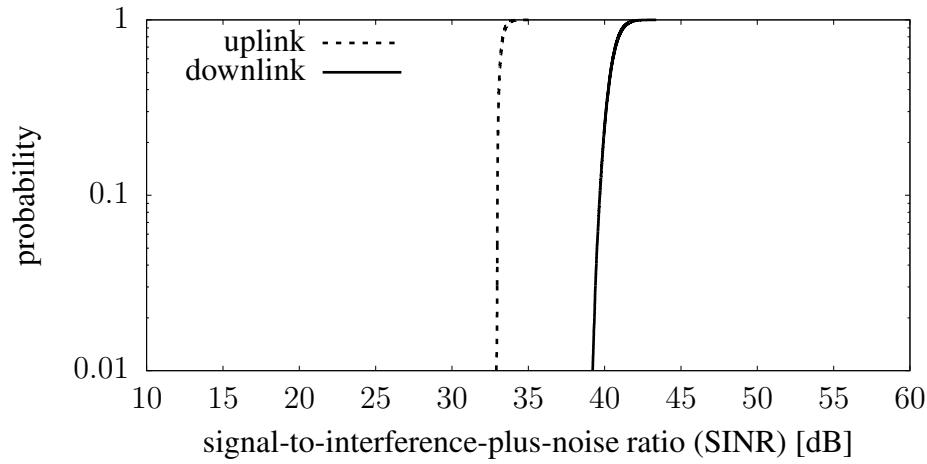
However, numerical experiments not disclosed here have shown that this effect is rather minor. Also, importantly, the effect is much larger for small numbers of base station antennas. Hence, insofar a required-number-of-antennas comparison is concerned, the inclusion of an orthogonal scheduling option would favor the PCS system much more than the mmWave system.

- Increasing the antenna separation beyond $\lambda/2$, or deploying the antennas with nonuniform spacing, improves channel orthogonality in some cases. This effect is more pronounced for smaller number of antennas, and hence primarily benefits the PCS system – at the cost of an increased physical size of the array.

However, the impact of larger-than- $\lambda/2$ or nonuniform spacing is relatively minor in most cases. The reason is most easily understood for a uniform linear array: Increasing the antenna spacing reduces the beamwidth but introduces grating lobes, and the total angular



(a) PCS ($f_c = 1.9$ GHz) system with $M = 128$ antennas.



(b) mmWave ($f_c = 60$ GHz) system with $M = 10000$ antennas.

Figure 2: Uplink and downlink SINR in the PCS respectively mmWave systems.

sector collectively covered by all grating lobes induced by beamforming in a particular direction is only weakly dependent on the antenna spacing.

- The mmWave system may utilize multiple antennas more readily at the terminals, resulting in a received power gain, as well as interference nulling capabilities.
- The mmWave system may have access to much larger bandwidths, although correspondingly higher radiated powers are required to exploit these bandwidths – as discussed above.

95%-likely SINR	Required number of antennas (M)		Array diameter (meter)	
	PCS (1.9 GHz)	mmWave (60 GHz)	PCS (1.9 GHz)	mmWave (60 GHz)
5 dB	46	256	1.2	0.20
10 dB	58	370	1.5	0.29
15 dB	75	571	1.9	0.45
20 dB	100	853	2.5	0.68
25 dB	135	1700	3.4	1.4
30 dB	177	5100	4.4	4.1

Table 2: Number of antennas, and resulting diameter of the circular array, required to obtain a given 95%-likely uplink SINR.

3 Conclusions

For a particularly simple scenario – line-of-sight propagation and perfect CSI – we find that, to attain comparable performance, considerably more 60 GHz antennas are needed. Some savings in mmWave electronics can be realized by employing hybrid beamforming that exploits the structure of line-of-sight propagation [15]. However any departures from our scenario are likely to result in a still greater antenna ratio.

Non-line-of-sight propagation would cause signals to attenuate at a rate much greater than in free space, with mmWave more disadvantaged than PCS. Merely to make up the greater path loss will require disproportionately more mmWave antennas. The angle spread associated with non-line-of-sight propagation will limit the extent to which hybrid beamforming may be used, thereby increasing the amount of mmWave electronics. Increasing angle spread also necessitates more frequent direct measurements of the propagation channels, a further disadvantage of mmWave technology, since the channels change at thirty times the rate of PCS channels.

Our line-of-sight analysis ignores mmWave signal blockage by the human body. To achieve 95% reliability, mmWave systems may have to utilize a large frequency reuse factor which proportionately reduces the effective available spectrum.

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